Investigation of Magnetic Force in Metallic Structureof Superconducting Magnet

A Thesis submitted in partial fulfilment of the requirement for the degree of

Master of Technology

In

Electrical Engineering

(Cryogenic and vacuum technology)

By

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Declaration

I endorse that

a) The work contained in the dissertation is original and has been managedby myself under the general superintendence of my supervisor.

b) The study has not been acceded to any other university for any grade ordegree.

c) I have adopted the guidelines offered by the Institute in writing thethesis.

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Certificate

This is to certify that the project entitled "**Investigation of Magnetic Force in Metallic Structure of Superconducting Magnet**" beingsubmitted by **Mr. Mukeshkumar**, Roll NO. 213ME5447 in the partial fulfillment of the requirement for the award of the degree of Master of Technology in Electrical Engineering with specialization in Cryogenic and Vacuum Technology is a research carried out by him at the department of Electrical Engineering, National institute of Technology Rourkela.

The result presented in this has not been, to best of my knowledge, submitted to any other university or institute for the award of any degree.The project in our opinion has reached the standards fulfilling the requirement for the award of the degree of Master of Technologyin accordance with regulation of the institute.

Date

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I would like to express my deep sense of respect and gratitude toward my supervisor Prof. B.D. Subudhi, who not only guided the academic project work but also stood as a teacher and philosopher in realizing the imagination in pragmatic way, I want to thank him for introducing me the field of optimization and giving the opportunity to work under him. His presence and optimism have provided an invaluable influence on my career and outlook for the future. I consider it my good fortune to have got an opportunity to work with such wonderful person.

Mukeshkumar

Abstract

The Weldestien 7-X, a steady state nuclear fusion reactor is being built by Max-Plank-Institute for Plasma Physics, Germany. In this, the superconducting magnets supply the required magnetic field to enclose the plasma. The steel plasma vessel and the helium cooled heat radiation shield are surrounded by superconducting coil. During discharge of the magnetic system, Eddy current is induced in the metallic structure. Due to complex geometry of the structure it is not possible to calculate the exact effect of magnetic force on metallic structure.

Therefore, in the present work mainly the magnetic field on and around the metallic structure due to the superconducting coils is analyzed using Ansys – Maxwell software. Using Ansys-Maxwelll 15.0, a toroidal metallic structure, surrounded by superconducting coils made up of aluminiumcryo-cooled at about 1 K is prepared. The software uses finite element method to calculate the magnetic force and intensity on metallic structure. The software divides the whole diagram into number of tetrahedral subparts and then solves each tetrahedral subpart in the form of matrices. Mainly the magnetic field on the surface of the metallic structure, the magnetic field vector on and around the surface of the metallic structure, the magnetic field intensity at different important points and sections of the metallic structure is obtained and analyzed. We can also find the vector diagram of magnetic field which clearly shows the direction of current and the intensity of field at each part of metallic structure.

Keywords: Stellarator, FEM, Superconductor, W 7-X, Fusion

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Chapter 1

Introduction

Stellarator type fusion experiments have been developed to provide an alternative method to the Tokamak steady state operation. It was planned to test and approve its relevance to the magnetic field confinement.During emergency discharge of large superconducting magnet the energy stored in the coils is discharged into external resistors [1].Due to this discharge magnetic field also decreases exponentially. According to Maxwell Equation

$$\nabla\times E = -\frac{\partial B}{\partial t} \tag{1.1}$$

Eddy currents are induced in the metallic structure. It means the current induces in plasma vessel and shield. Due to this induced eddy current magnetic force is developed,

$$F = J\times B \tag{1.2}$$

Second, the resulting heating has to stay within permissible limits to prevent the excessive thermal expansion of the material that would lead to damage. Hence, the knowledge of eddy currents and the resulting forces and heating in these structures is very important for the design of the plasma vessel and the 80K-shield of W-7X.The finite element method has already proved to be a powerful tool tonumerically solve electromagnetic field problems of arbitrary geometry.

Therefore a new modeling method is presented here which is based on Ansys-Maxwell software. The software usees finite element method to calculate the magnetic force and intensity on metallic structure. It divides the structure in to small tetrahedral part and then calculates the force on each part of structure. We can also find the vector diagram of magnetic field which clearly shows the direction of current and the intensity of field at each part of metallic structure. The software divides whole diagram in to number of tetrahedral parts and then solve each tetrahedral part in the form of matrices. It also shows the number of matrices used in solution and the memory taken by each matrices and the solution.

1.1Finite element modeling

Analytical method is not very exact in analyzing complex geometries like W 7-X. In such cases finite element method is found to be more relevant.In this method,the geometry of the model is discretized in to many small blocks. The FE model does not include the magnetic system. The model is excited via time dependent magnetic vector potential, which represents dynamic boundary condition. These conditions are applied to every single grid of the model by using method of Lagrange multipliers. FE method is used to calculate distribution of eddy current over the surface and power losses. For three dimensional problems, Ansys-Maxwell uses tetrahedral block as a basic element. Tetrahedral block is made of four nodes, one node at each corner.

There are three kinds of co-ordinate system used in FEM :

1. Natural co-ordinate
2. Local co-ordinate
3. Global co-ordinate

1.2 Motivation

In the present scenario, Coal, natural gas, oil and uranium are the major sources of energy. But the way we are using these fuels they are not going to last more than 500 years from today.To tackle future energy problems,huge research is going on and one of them is nuclear fusion experiment.It can supply energy for more than 100 million years. Thereforethe scientific fraternity is interested in nuclear fusion plant. Thetwo major projects on nuclear fusion areTokamak and W 7-X.

1.3 Objective

To study the behavior of magnetic field on metallic structure of superconducting magnets so that the magnetic force, magnetic field intensity, current density, field vector on every part of structure can be analyzed using Ansys-Maxwell 15.0 software.

1.4 Summary

- The W 7-X is used for steady-state operation.
- The stored magnetic energy is discharged in external resistor and due to this discharge the magnetic field decreases exponentiallyand eddy current induces in plasma vessel.
- Due to induced eddy current, a force is developed, $F = J \times B$.
- FEM is useful tool for finding stress on complex geometry.
- Using finite element method the force can be calculated.
- Ansys-Maxwell software is used for calculation of such forces.

Chapter 2

Literature review on W 7-X

The weldenstein 7-X is an advanced helical stellarator which produces confined magnetic field using superconducting magnet .This configuration is suitable for steady-state operation. The non-planar coil which is used in this stellarator provides both toroidal and poloidal field to achieve the necessary field lines. The optimization process led us to divide the torus into five equal parodic modules which is surrounded by non-planar coils. And field varies between 3 T to 6.7 T at plasma axis field magnitude is about 3 T and on conductor surface the value of field is 6.7 T. This magnetic field can be achieved by using superconducting coil made of NbTi. The W 7-x provides 10 MW of heating power at 140 GHz frequency. The Wendelstein 7-X (W7-X) is presently 2nd largest fusion project, which is under construction of Max-Plank –Institute of Plasma Physics Greifswald, Germany. [17]

The W 7-x is constructed in two stages, in first stage they allow short pulse operation at full power using simple adiabatic diverter and the construction was completed in 2014. In the second stage, planer coils are designed. The solution of critical issues in W 7-X design are prediction based, it is predicted on behavior of system. [18]

The W-7-X is equipped with various components like a high power heating system, superconducting magnet, water cooling plasma components and diverter. The stellarator is designed for steady-state operation with input power of 10 MW. Its pulse length can go up to 30 minutes with maximum peak power of 20 MW for 10 seconds. Power facing component and water cooling system are designed for providing exhaust power and particle flux for the steady state operation. To study different phases of plasma, analysis is done for short pulse duration only [19].

Current leads with HTS component is made up of Bi-223 material.Its operating temperature range is form room temperature to 60-70 K while the value of magnetic field in the current lead region is below 0.5 T.This construction of current lead is successfully done by Karlsruhe Institute of Technology. The up-down orientation feature of the current lead can cause serious problems for stable and optimal operation of heat exchanger due to occurrence of free convection inside heat exchanger. Because HTS and helium are used so it will reduce the risk. The heat exchanger covers the temperature range between 60 k to room temperatureand superconductor part covers the range of 4.5 K to 60 K by means of conduction. The material used in current lead is made of Bi-2223/AgAu and its critical current is greater than 110 A at 77 K temperature. There are 14 current leadswith nominal range of 14 KA to 18.2 KAare used. [20]

W 7-X is designed for steady state operation but its heat rejection capacity is limited to 30 minutes only. The stellaratorconsists of five equal modules and every module has a weight of about 150 tons with 254 portsthat connect plasma vessel to the outer vessel. The steel plasma vessel and the helium cooled heat radiation shield are surrounded by superconducting coil. During discharge of the magnetic system, Eddy current induces in the metallic structure. Due to complex geometry of the structure it is not possible to calculate the exact effect of magnetic force on the metallic structure. [21]

Chapter 3

Process concept and description

3.1 Nuclear fusion

Thermonuclear fusion is the process by which nuclei of low atomic weight such as hydrogen combine to form nuclei of higher atomic weight such helium.

Fusion of two nuclei with lower masses then iron (Fe 26) generally release energy while nuclei heavier then iron absorbs energy. During the process of nuclear fusion some of the mass is converted in to heat energy and this is the most basic form of the energy in the universe.

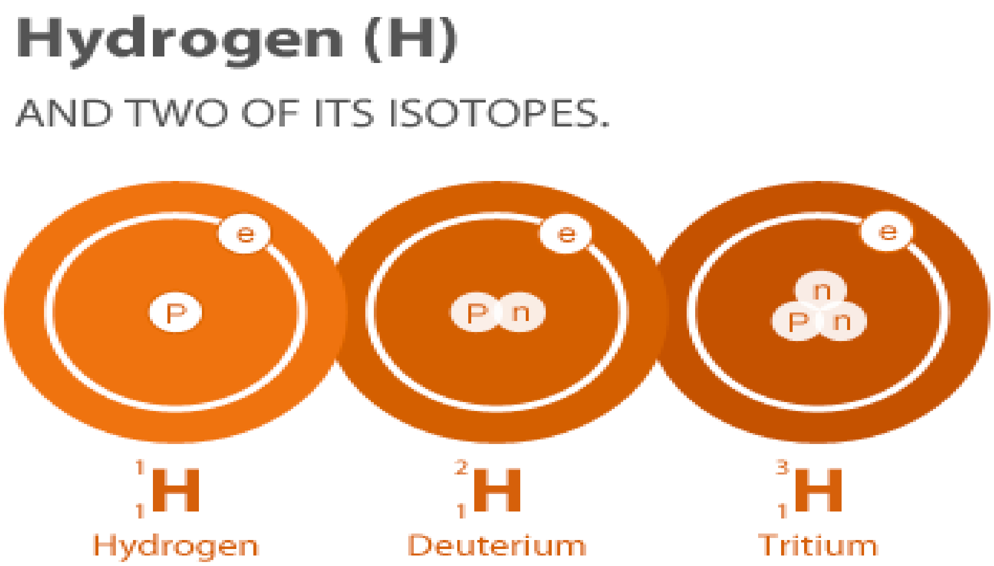

Figure 3.1 two isotopes of hydrogen Deuterium and Tritium [22]

Hydrogen is mostly used of fusion reaction because it two isotopes provide very favorable environment for reaction; first isotope is Deuterium (It contains one neutron one proton) and second is Tritium (It contains two neutron and one proton).

In the fusion process some of the mass of the original nuclei is lost and transformed to energy in the form of high energy particles. Energy from fusion reactor is most basic form of energy in the universe.

Fusion occurs mostly in stars due to hydrogen (H_1& H_2)

- Ionized hydrogen atoms repealed each other.
- Hydrogen atoms are heated by heat of stars.
- Nuclei travel so fast they drive through repulsive electric field

Fusion reactors use specific isotopes of hydrogen as a fuel because these can react at very useful range for energy production. Most of reactors are using deuterium and tritium. For preparation of fusion these isotopes are heated so that they become plasma. Plasma is a heated gas consisting of free electrons and nuclei which is not bound in to atom and it is a different state of matter along with solid, liquid, and gases. This allowsthe atomic nuclei to be separated out. Science the deuterium and tritium ions are positively charged they are try to repel each other due to strong electro static force. For fusion reaction this repulsion must be overcome forcing these lighter nuclei close enough together for collision. the fusion plasma must be confined and kept clean for long sustain of fusion reaction.

3.2 Challenges of using fusion

Fusion process need to done at very high temperature so that the element becomes plasma.

There are three ways to heat the plasma

1. Gravity
2. Inertia
3. Magnetic

Magnetic confinement is used magnetic and electric field to heat and squeeze the hydrogenPlasma. Two super imposed magnetic fields enclose the plasma. In magnetic confinement approaches to fusion reaction, magnetic field hold the plasma in isolation while very high temperature with a very high speed of nuclei and create a necessary collision.

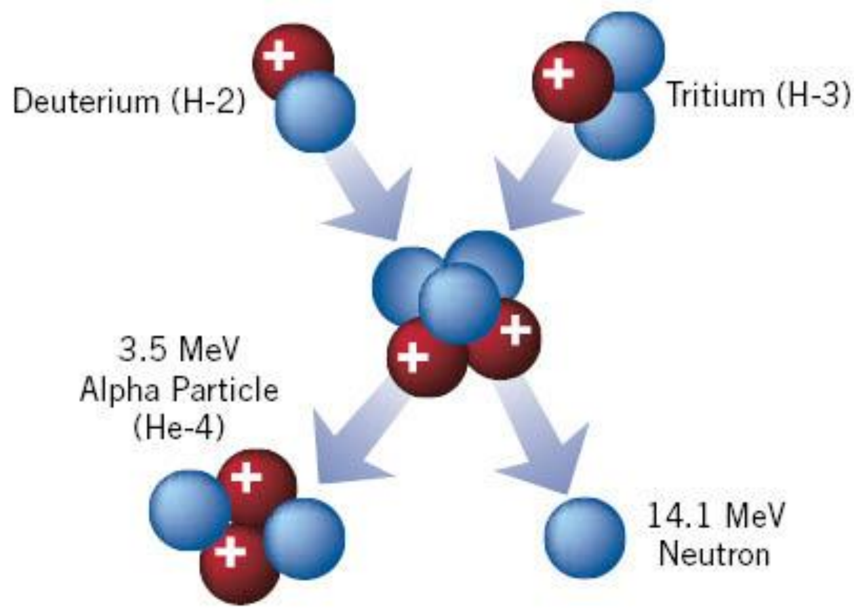

Figure 3.2- Fusion reaction of deuterium and tritium[22]

After The fusion reaction between deuterium and tritium helium nucleus produce and a single neutron with 14.1 MeV (2.82×10^{-12}) of energy. Even after generation of extremely high temperature needed to initiate nuclear fusion, there are no such materials which can withstand at such higher temperature.

One solution to this is to keep the hot plasma out of contact with the wall of container by keeping it moving in circular or helical path.

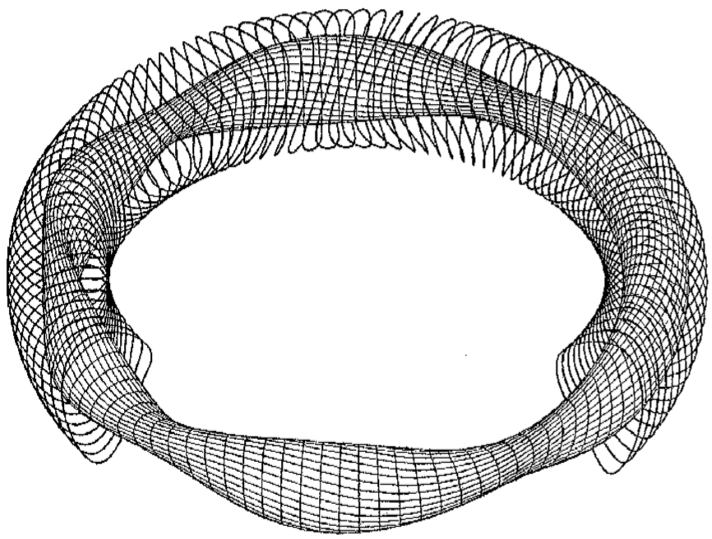

Figure 3.3-superimposed magnetic field[2]

3.3 Summary

- The working principle of W 7-X is based on nuclear fusion.
- Where hydrogen element deuterium is used as a fuel.
- Fusion is need to done at very high temperature so that the element becomes plasma.
- The temperature requires for hydrogen to become plasma is 10000 K.
- Electric and Magnetic field is used to heat and squeeze the plasma

Chapter 4

Wendelstein 7-X setup

The Wendelstein 7-X is made up of five similar modules which are in pentagonal shape torus. Every segment consists of two share out which are symmetrical with respect to a large torus radius vector. The module have 20 planer coils and 50 non-planers coil which are not in circular shape and these coils are made of superconductor. The entire system is placed in one common cryostate. The inside wall of the cryostate is made by the plasma vessel containing of 17 mm we can see in figure1 and figure 2steel

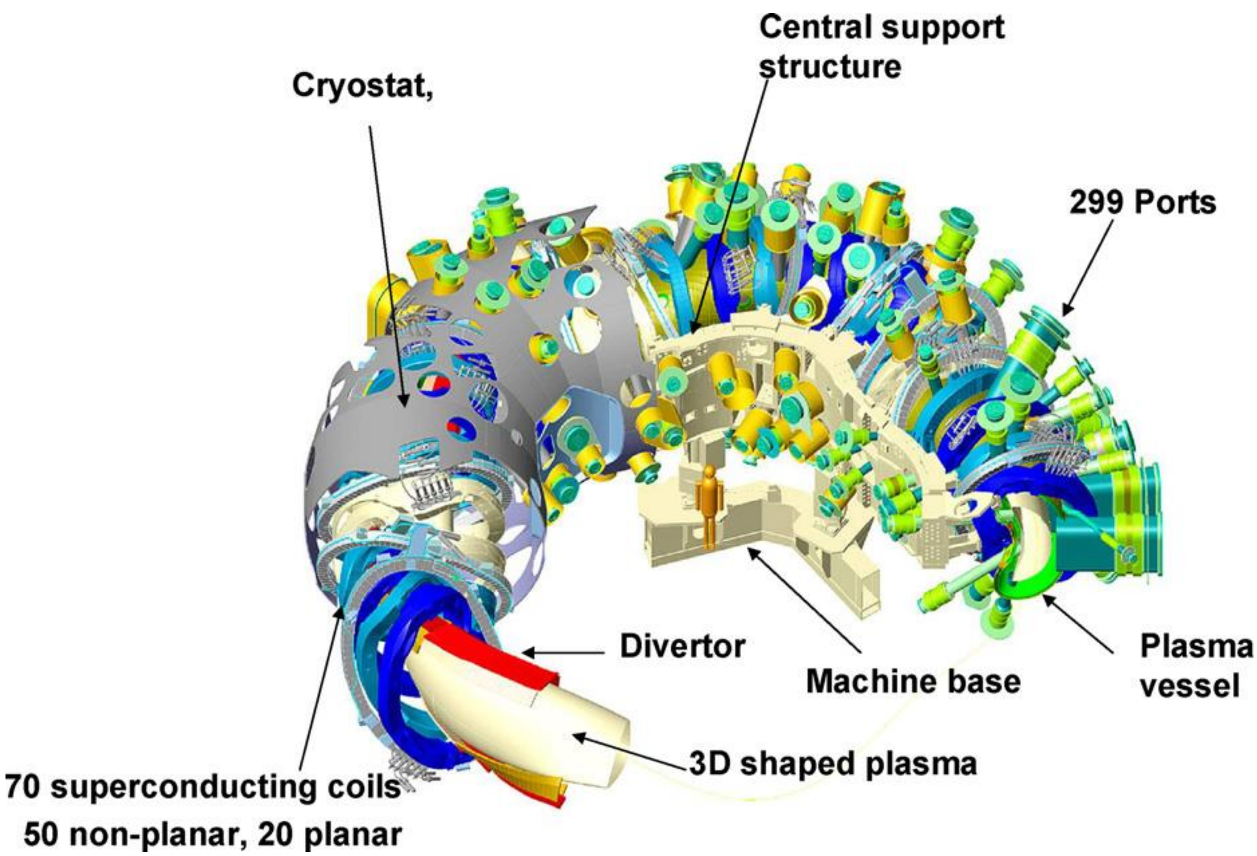

Figure 4.1-Wendelstein 7-X [15]

The metallic 80K-shield which is cooled by helium prevents heat radiation from the plasma vessel to the coils at cryogenic temperature.

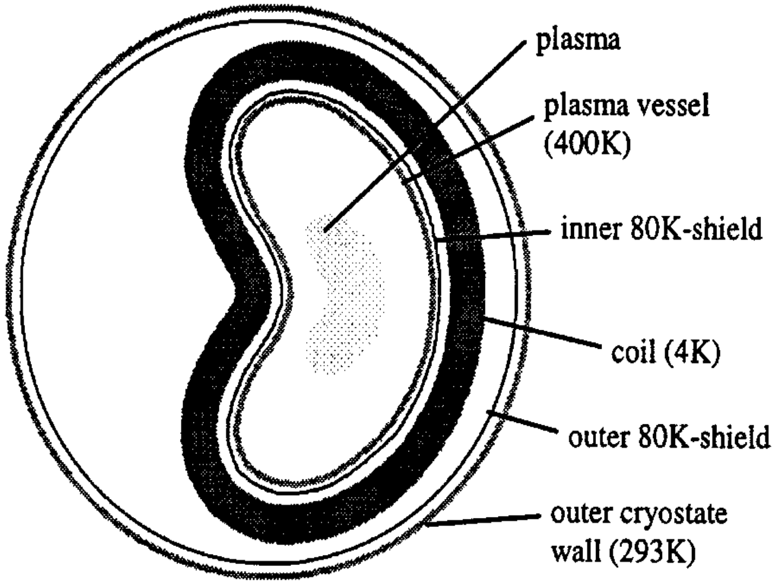

Figure 4.2- Cross-section of cryostate [2]

In a first method a 2mm copper shield was used.This was separated into many panels and these are separated from each other and the plasma vessel to obstruct the flow of eddy current. There are two additional method is to reduce the eddy current. Firstly mechanical stress should be kept as possible as low and the first possibility is to further divide the panels into four strips that are also insulated against each other.

The second option is to use a composite material containing of a 1 mm coat of steel and a 0.3 mm coat of copper. These materials have a lower electric conductivity but the mechanical strength is improved. These two methods are also to be examined in the work.

Almost every superconductor is using the same type of superconducting material. It is a forced flow cable and conductor NbTi used. Cable with 243 strands is used which is enclosed by aluminum cover with a void ratio of 37 %. The external dimensions of the cover are 16 mm x 16 mm. The design of three dimensional coils directed to the supplies of a bending with a minimum bending radius of 120 mm. The conductor cover should be soft enough to allow the winding work during the coil manufacturing and it should be enough stable to transfer the load during process. So the aluminum alloy (AIMgSiO.5) was chosen as cover material. The coil strands are made of NbTi materials withdiameter of 0.57 mm and all are stabilized by copper with non-copper ration of 2.6.The critical current specification of superconductor is 35 kA at 4 K and 6 Tesla background field this gives a temperature margin of about 1 Kelvin for the coils throughout process.

4.1 Planer coils

For the change of configuration of magnetic field the planner coils are used e. g. in terms of shear, jota and mirror. The planar coils are wounded over the non-planar coils at an angle of about 20 degrees with respect to the main vertical axis. There are 20 planar coils are used which are of two different types and the types are Type A and Type B with 10 coils each.These coils have outer diameter of 4 meter and the weight around 4 tons. The current rating of these coils is 16 KA. The coil insulation system is designed for a nominal voltage to ground of 4 kV d. c. and a related test voltage of 9 kV d. c. during the receiving test at room temperature. The leading components of the planar coils are the winding pack, the steel case, the case cooling system and the lead and instrumentation area.

4.2 Superconductors

Super conductors are materials of extraordinary electrical and magnetic behavior. They show perfect conductivity and perfect diamagnetism. Perfect conductivity means zero resistance and hence there are no power losses in superconductor. Perfect diamagnetism means very strong repulsion in magnetic field and this means generation of strong force against gravitational force.

Super conductivity can be achieved at very low temperature or cryogenic temperature.

When metal is cooled, its electrical conductivity increases. Because at room temperature resistance is due to scattering of electron by vibration of atoms in lattice with high amplitude and at low temperature the atom vibrate with small amplitudes and so scattering will be reduce which is resulting low resistivity.

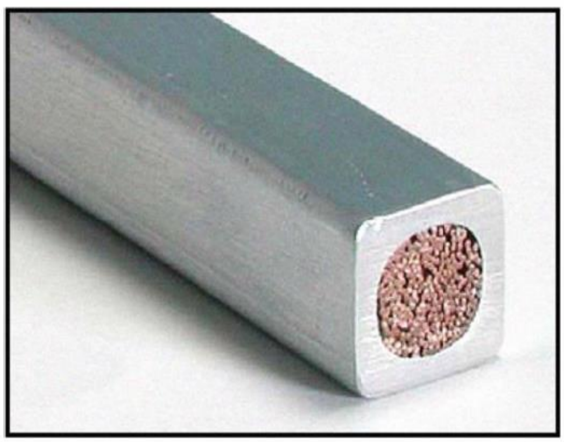

Figure 4.3- Nb-Ti conductor [6]

The magnetic fields which are needed to enclose the plasma are to be supplied by superconducting coils. The conductor used NbTi. It consists of a cable with 243 strands enclosed in an aluminum-alloy jacket. The main magnetic field of W7-X will be achieved by the nonplanar coils. The planar coils in W7-X are used to change the magnetic configuration. The planar coils are assembled over the non-planar coils.

The current leads are used to connect inside and coils and these coils are connected through superconducting bus bar. It also provide the flow of current from room temperature bus bar to superconducting part of inside conductor. The total quantity of superconductor was about 60 km, made of about 15000 km of strands.

4.3 Summary

- The stellarator fusion experimental device
- To allow the steady-state operation, W7-X has a superconducting magnet system.
- The superconducting magnet system consists of 50 nonplanar coils, 20 planar coils, a superconducting bus system, and 14 current leads.
- They are arranged toroidally in five equal modules
- The magnetic fields which are needed to enclose the plasma are to be supplied by superconducting coils
- conductor used NbTi
- It consists of a cable with 243 strands enclosed in an aluminum-alloy jacket
- The main magnetic field of W7-X will be achieved by the nonplanar coils
- The planar coils in W7-X are used to change the magnetic configuration
- The planar coils are assembled over the non-planar coils

Chapter 5

Ansys-Maxwell

Maxwell 3D is a high-performance interactive software package that uses finite element analysis(FEA) to solve electric, magnetostatic, eddycurrent,and transient problems. Ansys-Maxwell is very useful product for solving the problem related to magnostatic.it is very user friendly for solving complex magnetic problem.Maxwell solves the electromagnetic field problems by solving Maxwell's equations infinite region of space with appropriate boundary conditions.The current project is based on magnetostatic problem so I am going to describe about this solver working principle.

5.1 Maxwell solution types

- Magnetostatic: we can find the solution related to static magnetic field and calculate the torque, force and inductance caused by dc currents, static external magnetic field. For linear and non-linear materials.
- Eddy current:we can calculate sinusoidal varying magnetic field, torque, force, impedance caused by alternating current, and oscillation of external magnetic fields for linear materials only. It also includes skin effect and proximity effects.
- Transient magnetic: we can also calculate the transient magnetic field which is caused by time-varying or moving electrical source and permanent magnet. For linear and non linear materials. It also includes skin effect and proximity effect. We can use DC, AC, or transient current or voltage as a source.

- Electro static – we can calculate static electric field force, torque, and capacitance cause by voltage distribution and charge. Used for linear material only.
- DC conduction: we can calculate voltage, current density and electrical field.conductors which is surrounded by insulators can be added to the simulation and electric field can be calculated everywhere including insulators.
- Transient electric: we can calculate transient electric field caused by time-varying voltage, charge distribution in homogeneous material.

5.2 Magnetostatic material property

The following parameter is required for such materials

- **Relative permeability (μ):** it can be linear or nonlinear and is define as μ_{0*} μ_r. Relative permeability and coercively determine the magnetic problem of material.
- **Bulk conductivity:** it is used to determine current distribution in current carrying conductor and it has no impact on any part of analysis.
- **Magnetic coercivity:** it is used to define permanent magnetization of material. Its magnitude and direction should specify.
- **Composition:**it can be solid or lamination and used for creating anisotropic magnetization effect**.**

5.3 Assigning boundary condition

- **Default:** when no boundaries are assign for surface there are two kind of treatment can be assigned**.**

  Natural: magnetic field intensity (H) is constant across boundary.

Neumann: magnetic field intensity (H) is tangential to boundary and flux cannot cross it.

- **Insulating**: magnetic field intensity (H) is tangential to boundary and flux can cross it and also used for insulation for two conductors.
- **Master/Slave**: it is used to reduce design size and the boundary condition matches the magnetic field at the slave boundary to the field at the master boundary based on U and V vectors**.**
- **Symmetry boundary:**user can model the part of structure, which reduce the size and complexity of design and it's shorting the solution time.

5.4 Excitations

- **Current:** current defines in Amp-turns through the conductor. Stranded conductors can also be used.Current can be assigned to conductor face that lies on boundary of simulated domain or sheets that lie inside the conductor completely.
- **Current density:**current density used to define a known current density of conductor by using X, Y and Z components.
- **Current density terminal:** the terminal is required to define if current density defined.

5.5 Parameters

The parameters should be assigned for magnetostatic solver to calculate force, torque and matrix using magnetic field solution.

- **Force**: we can calculate the force on assigned body. Force can be Virtual or Lorentz.
- **Torque**: we can calculate the torque on assigned body. Force can be Virtual or Lorentz.
- **Matrix**: it can calculate the no of matrices solve in object.

5.6 Analysis setup

The solution setup defines the parameter which is used for solving the simulation. We can have multiple setups in the same design.

5.7 Summary

- Maxwell 3D is a high-performance interactive software package that uses finite element analysis(FEA) to solve electric, magnetostatic, eddycurrent,and transient problems.
- Maxwell solution types: It can solve electrostatic or magnetostatic problems.
- Model Design: User has to design the model which is want to solve.
- Magnetostatic material property: Material can be linear or non-linear.
- Assigning boundary condition: Choose appropriate boundary condition.
- Excitations: Excitation can be current or voltage.
- Analysis setup : after putting all the necessary condition we can analyzed the result.

Chapter 6

Results and Discussions

For the analysis of magnetic field, a torus is designed in Ansys-Maxwell. The torus is made up of Steel_1008.The major radius of the torus is 78 mm while the minor radius is 28 mm.

In the present analysis, 20 superconducting planar coils are used to generate necessary magnetic field.The superconducting planar coils are made up of aluminium. The critical temperature of aluminium is 1.7 K whereas 1 K temperature is used to simulate the system in Ansys-Maxwell. The critical Magnetic field for aluminium is 15 T whereas a magnetic field of 9 T is used to simulate the system. The critical magnetic field can be calculated using the following equation

$$Bc = Bc(0)\left[1 - \left(\frac{T}{Tc}\right)^2\right] \tag{6.1}$$

The value of critical current is about 4904 A wheras the current used to simulate the system is 5000 A.The critical current can be calculated using the following equation

$$Ic = \frac{2\pi r Bc}{\mu o} \tag{6.2}$$

Specification	Value used
Core material	Steel
Major radius of core	78 mm
Minor radius of core	28 mm
Number of planer coil	20
Coil material	Aluminium
Temperature of coil	1 K
Boundary condition	Insulating
Excitation current	120 A
Convergence	50 %
Maximum No. of passess	10

Magnetic field on surface

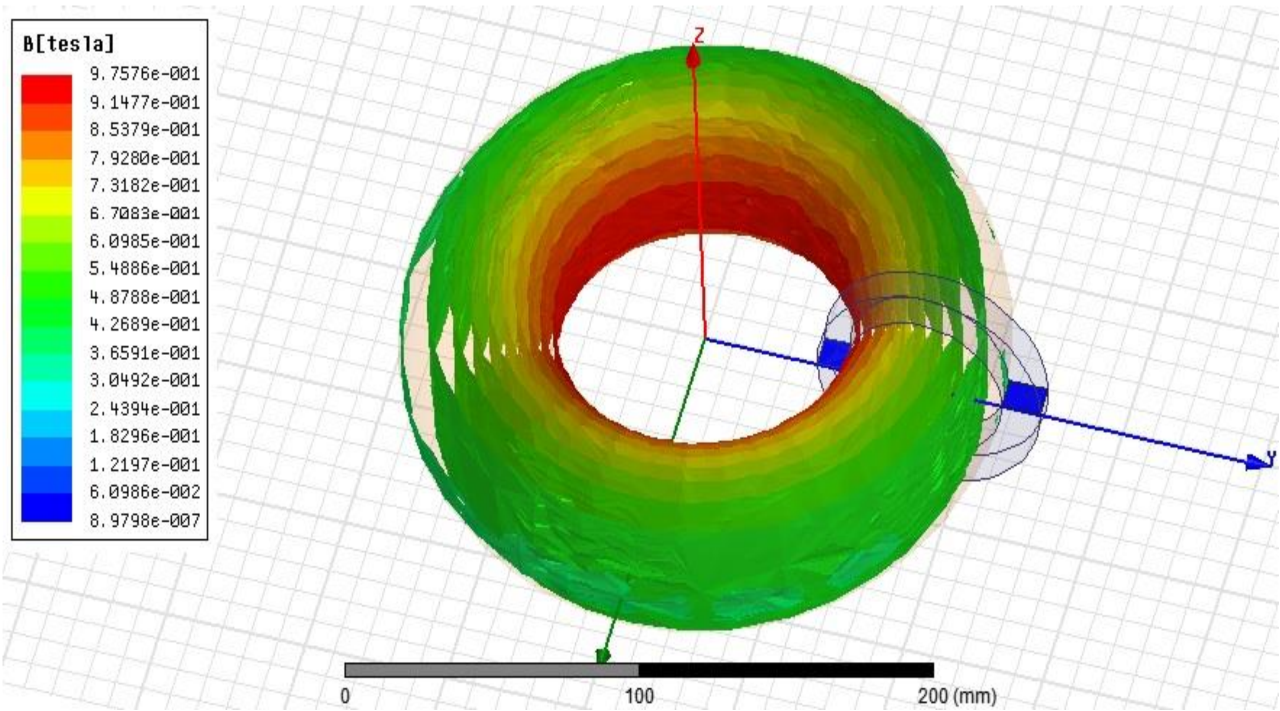

Figure 6.1Magnetic field on surface using single conductor

Figure 6.1 shows magnetic field on surface of mettalic structure using single conductor, there is huge variation of field in the structure, red color shows maximum field while Blue color shows minimum field the variation of field from 3.5 T to 8.11 mT. The value field is maximum in side the core and minumum at surface of coil.

Original magnetic field produced by Max-Plank Institute

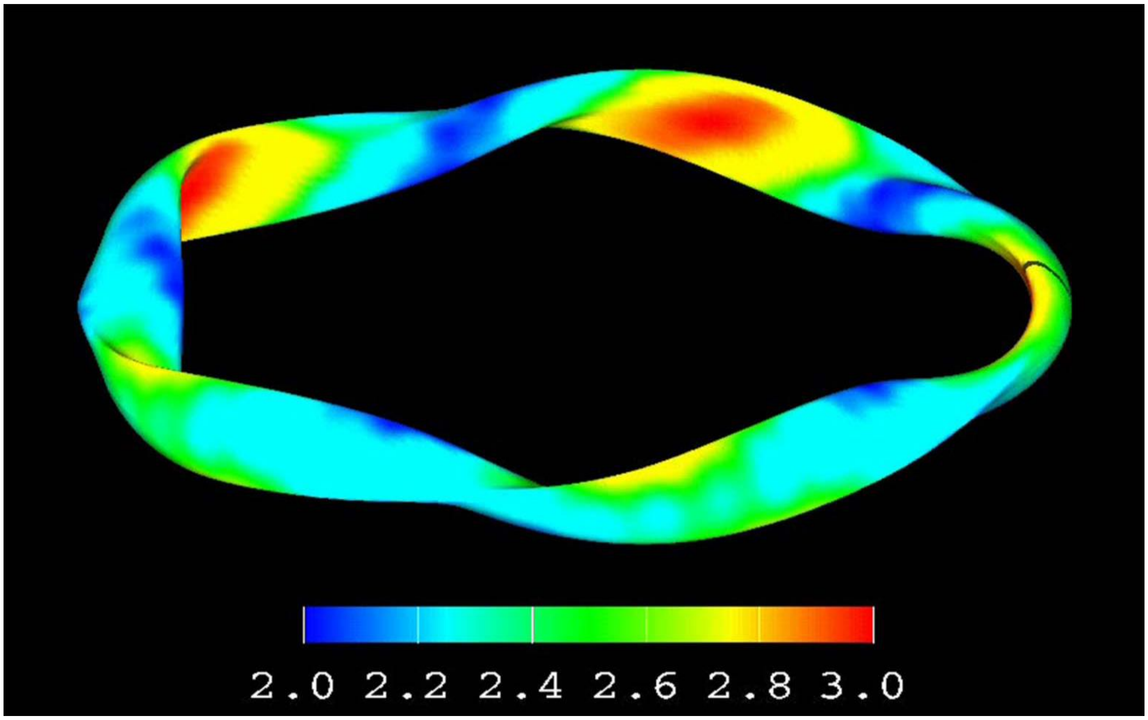

Figure 6.2-Original magnetic field produced by Max-Plank Institute

Figure 6.2 shows the original digarm of which is generated by Max-Plank Institute, Germany. In this figure magnetic field is uniformly distibuted over surface, the maximum value is 3 T and minimum 2 T, there is no much difference in field which is produced by using super conducting magnet.

Magnetic field on sectional view

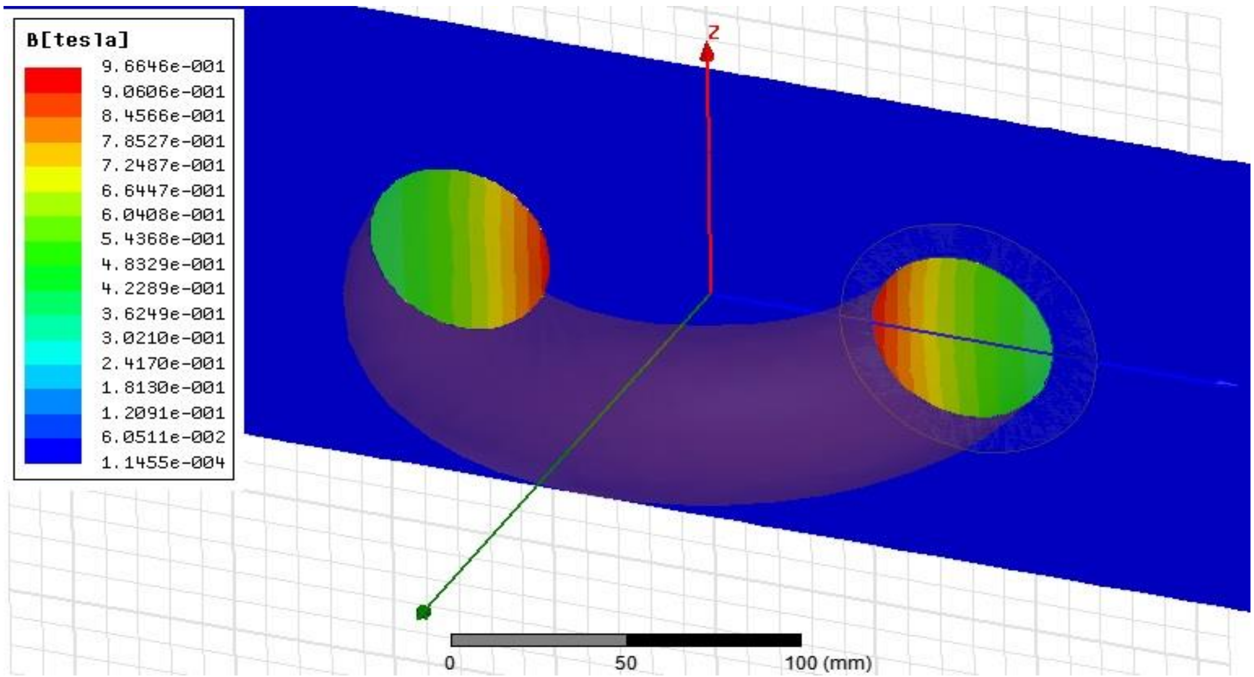

Figure 6.3 magnetic field section view using single conductor

The above figure 6.3 shows the magnetic field intensity on the mettalic surface of conductor, we also have a sectional view in figure which is showing magnetic field intensity on different part of mettalic surface. the red color show higher intensity while blue color shows lower intensity . we can also compare it with original magnetic field which is produced by max plank institute in figure.

Magnetic field vector

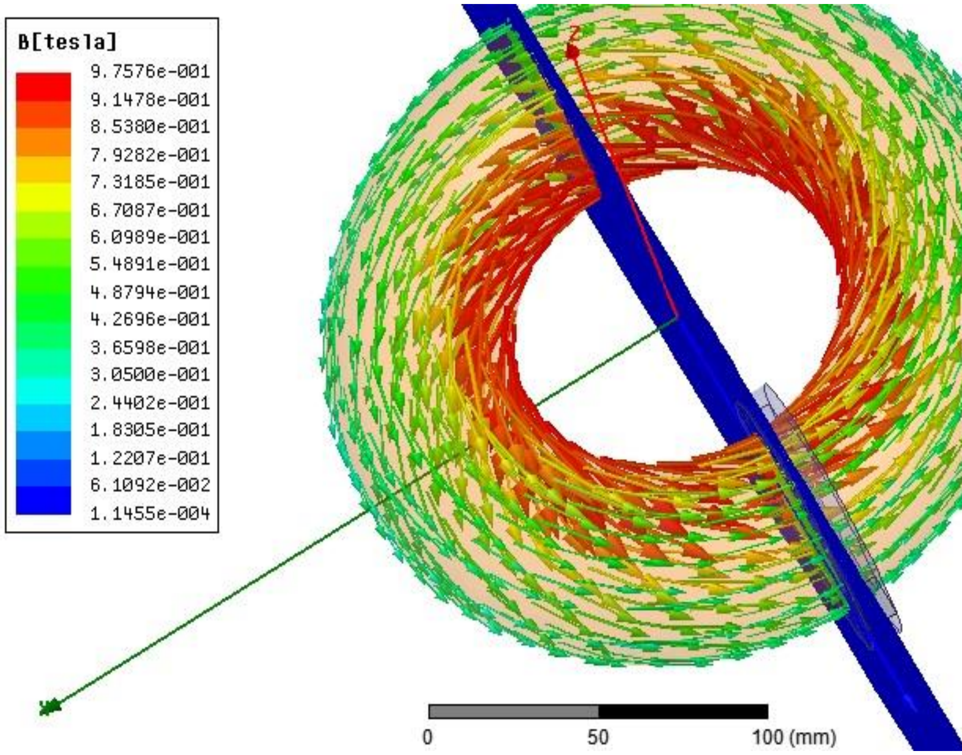

Figure 6.4 magnetic field vector using single conductor

The above figure shows the magnetic field vector which is in anti-clock wise direction which also can be find by Fleming thumb rule. If we put our thumb in direction of current and curl our finger then it shows the direction of magnetic field.

Meshing

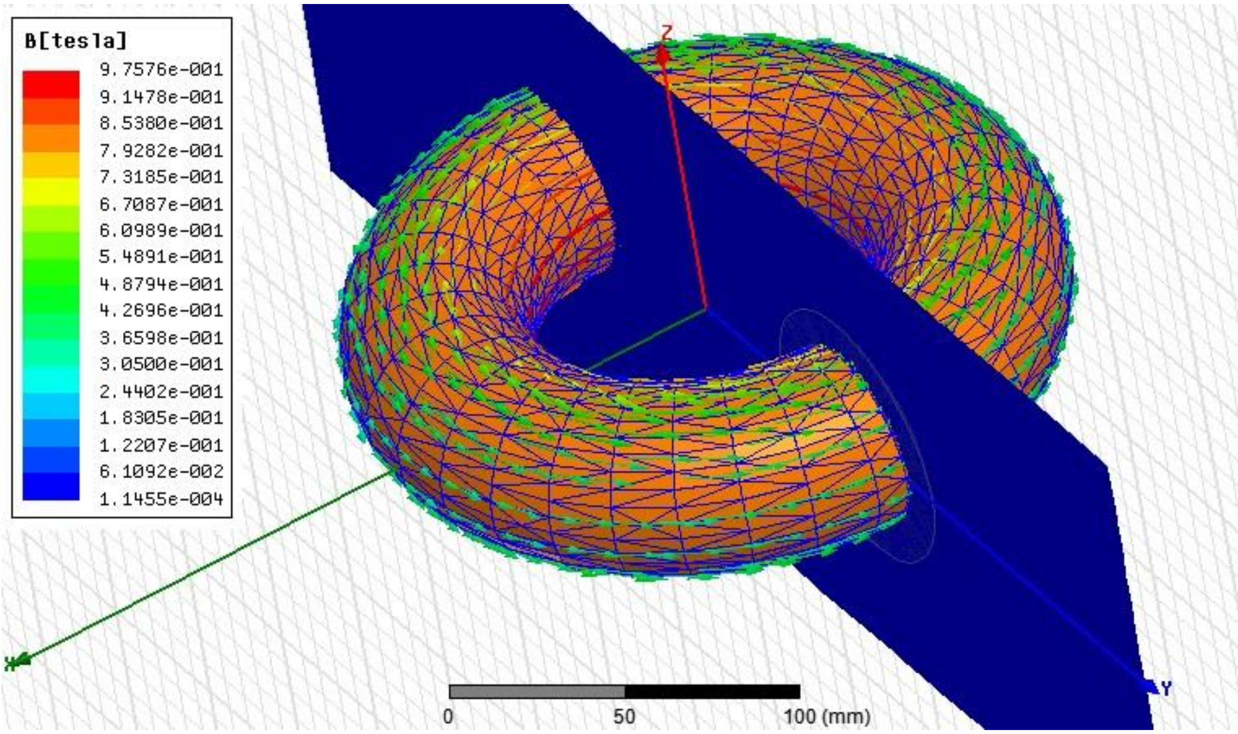

Figure 6.5 meshing using single conductor

The above figure shows the meshing on the metallic surface which is in tetrahedral shape. The total number of tetrahedral is 17672.higher the no. of tetrahedral the graph will be more confine.

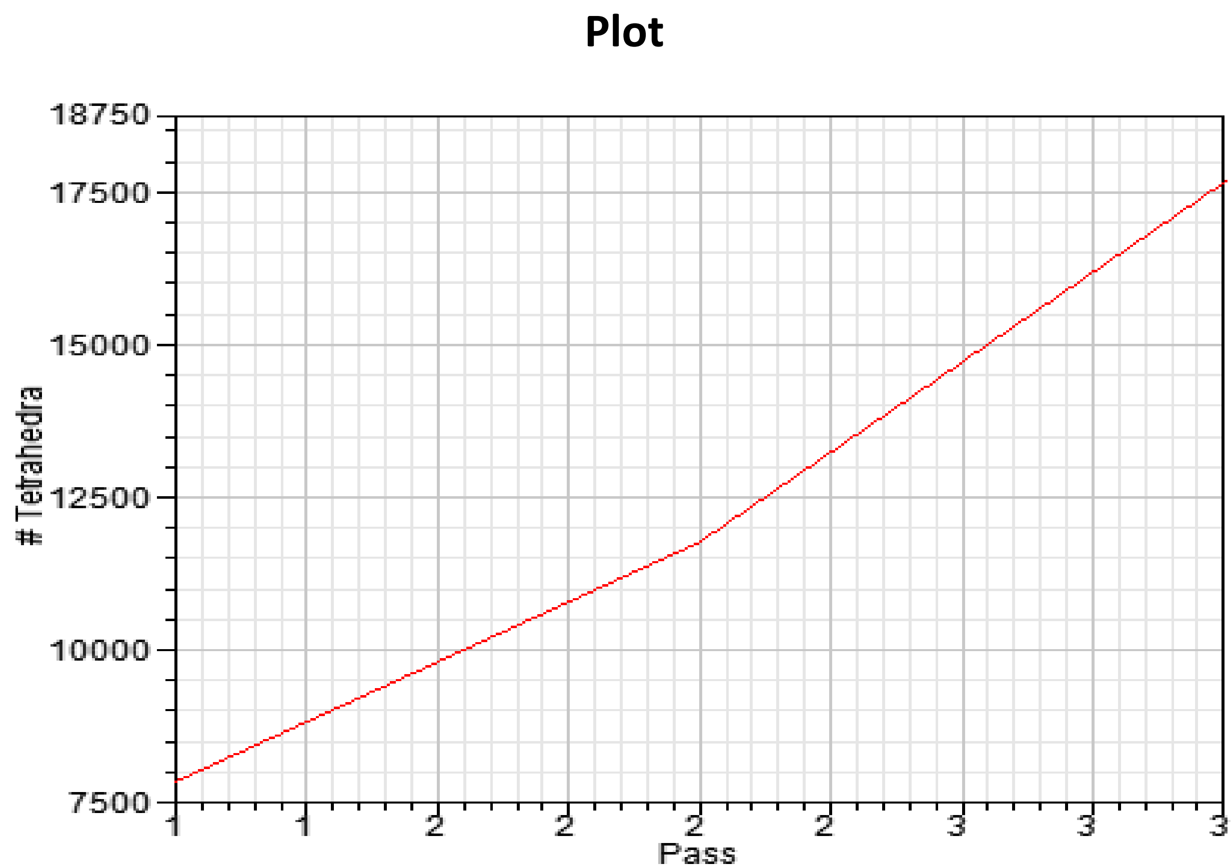

Figure 6.6 plot using single conductor

Number of tetrahedral increased with increased in number of passes so the error will decreased.

The total number of tetrahedral is 17672 with 3 numbers of passes.

Solution data

Profile | Convergence | Force | Torque | Matrix | Mesh Statistics

Task	Real Time	CPU Time	Memory	
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
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Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	90 K	410 matrix, 0KB disk
Solver DRS	00:00:02	00:00:02	77.8 M	24247 matrix, 0KB disk
Solver DRS	00:00:02	00:00:02	77.8 M	24247 matrix, 0KB disk
Solver DRS	00:00:03	00:00:01	77.8 M	24247 matrix, 0KB disk
Solver DRS	00:00:02	00:00:01	77.8 M	24247 matrix, 0KB disk
Solver DRS	00:00:01	00:00:01	77.8 M	24247 matrix, 0KB disk
Solver DRS	00:00:01	00:00:01	77.8 M	24247 matrix, 0KB disk
adapt	00:00:11	00:00:10	103 M	17672 tetrahedra
				Adaptive Passes Converged
Solution Process				Elapsed time : 00:00:54 , Maxwell ComEngine Memory : 41 M
Total	00:00:33	00:00:31		Time: 04/01/2015 00:59:44, Status: Normal Completion

Figure 6.7 solution data using single conductor

The solution data is showing about time taken in conversing of solution it also tell about number of matrices solved during the conversion of solution and the memory used by those matrices which is shown in above figure.

Magnetic field on the surface of metallic structure Using 20 planer coils.

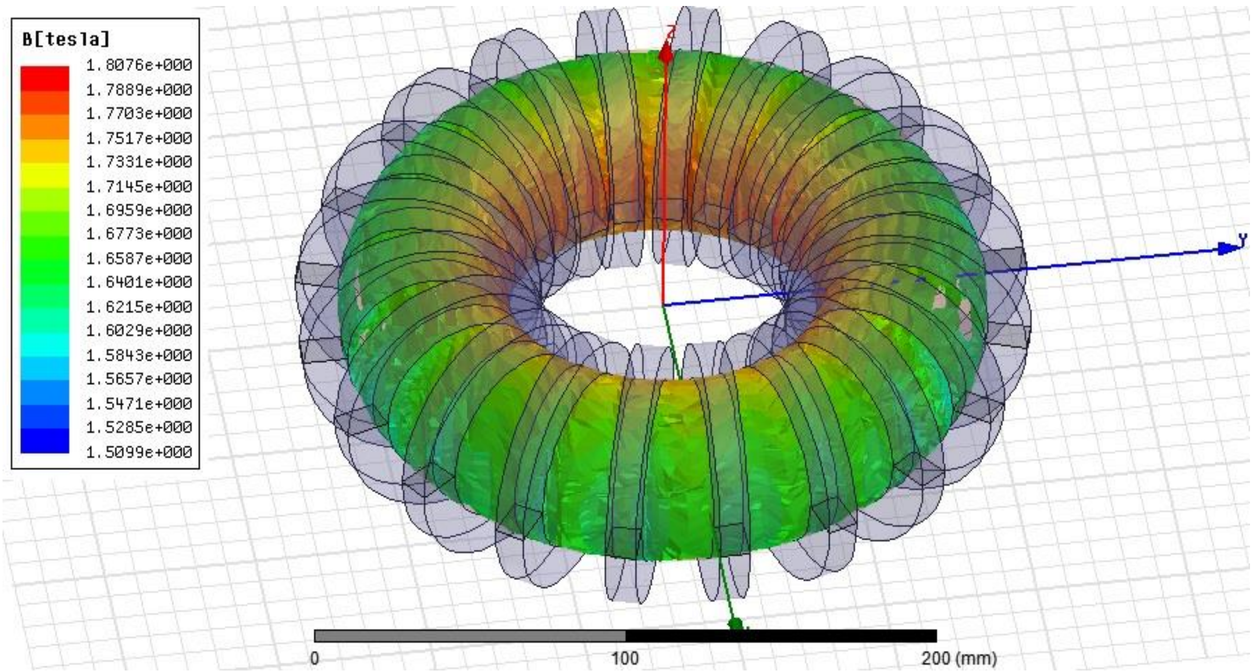


Figure 6.8-Magnetic field on the surface of metallic structure using 20 coils

The above figure shows the magnetic field on the metallic structure using 20 planer coils. The red color shows higher magnetic field which is 1.8 Tesla and the blue color shows lower magnetic field which is 1.5 Tesla. There is no much difference in higher and lower magnetic field around the whole surface of structure this is the advantage in using 20 coils.

Magnetic field vector

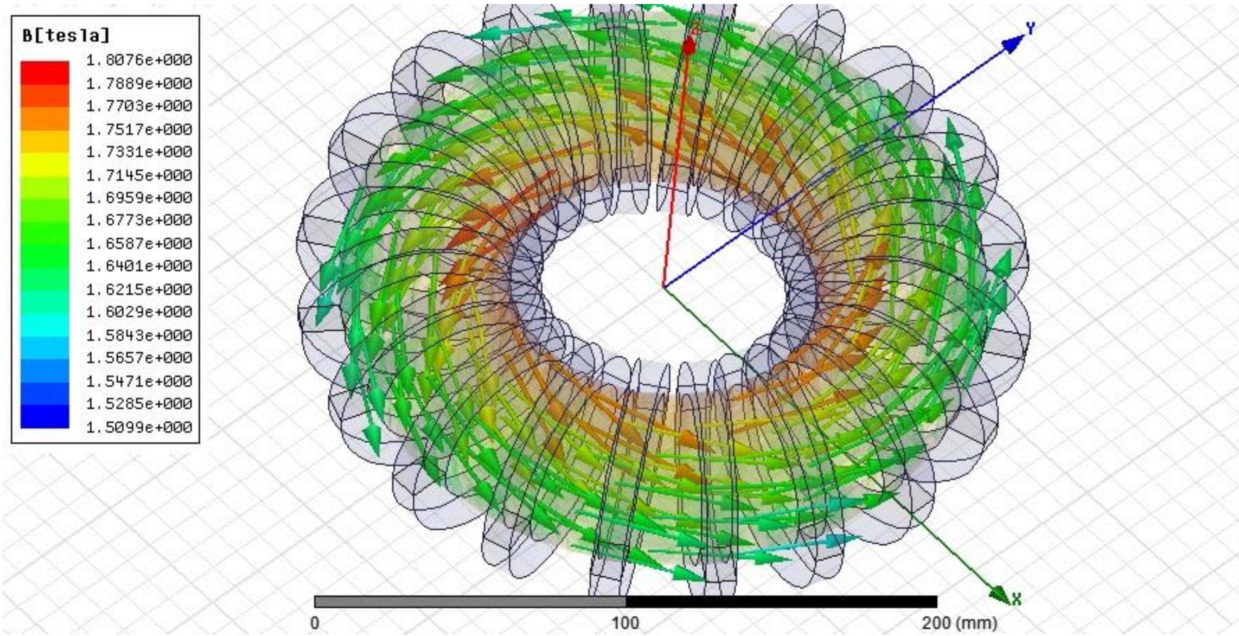


Figure 6.9- magnetic field vector using 20 coils

We have the figure which shows the magnetic field vector and the direction of magnetic field is anti-clock wise obtain by Fleming thumb rule.

Magnetic field vector sectional view

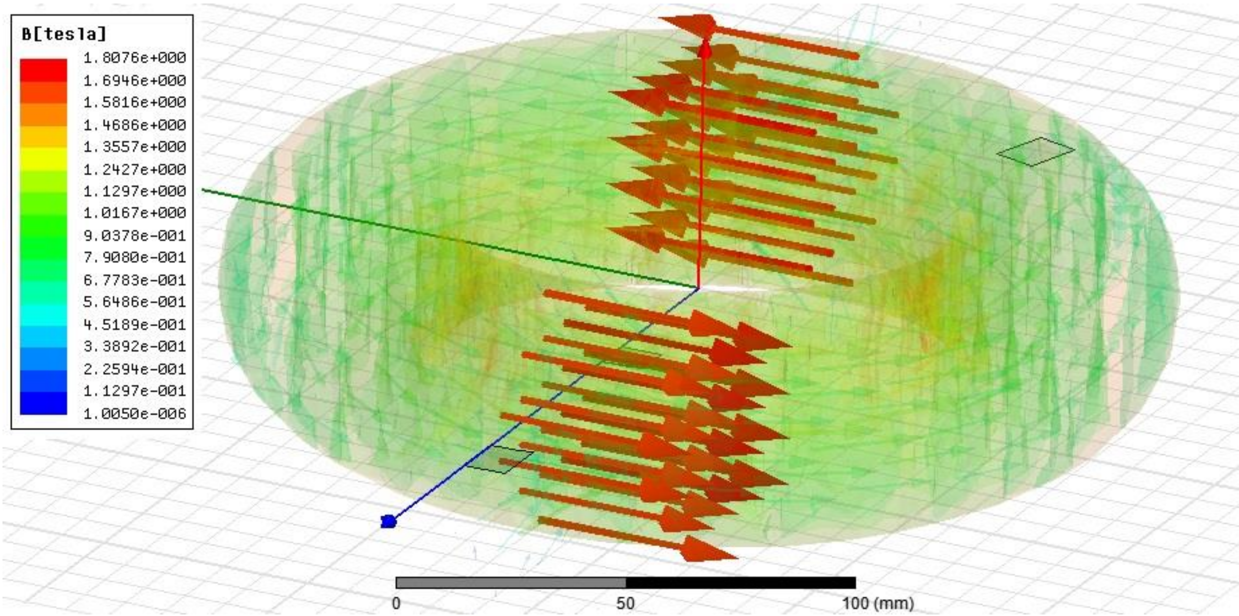


Figure 6.10-Magnetic field vector sectional view using 20 coils

Magnetic field intensity

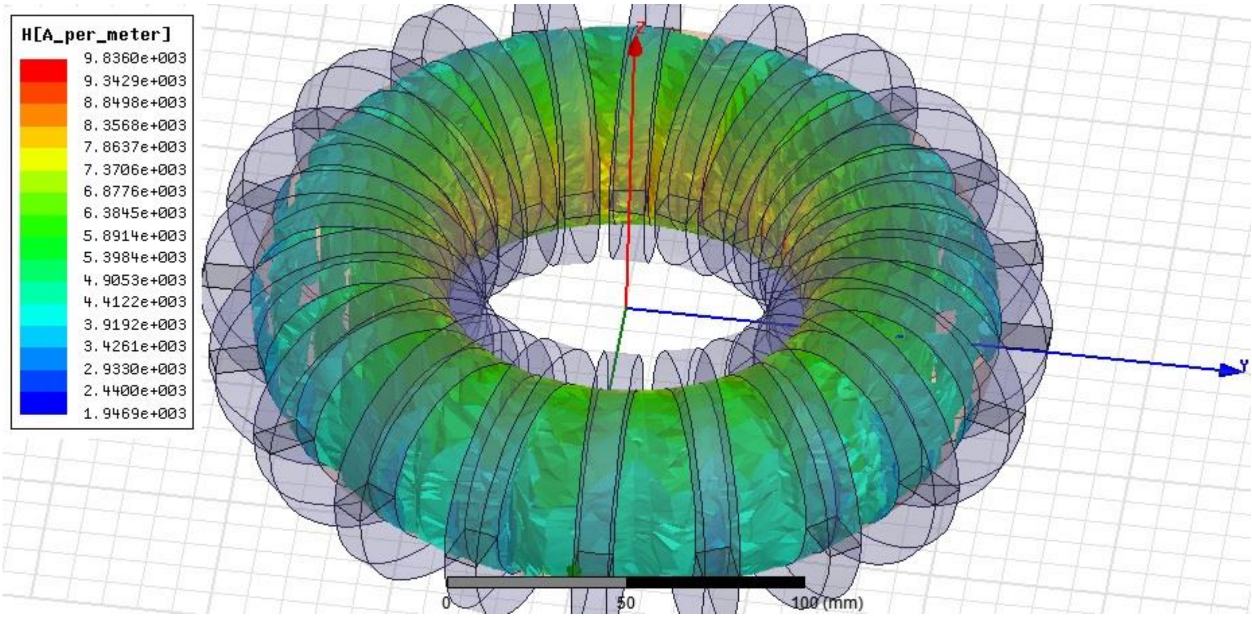


Figure 6.11-Magnetic field intensity using 20 coils

Magnetic field intensity section view

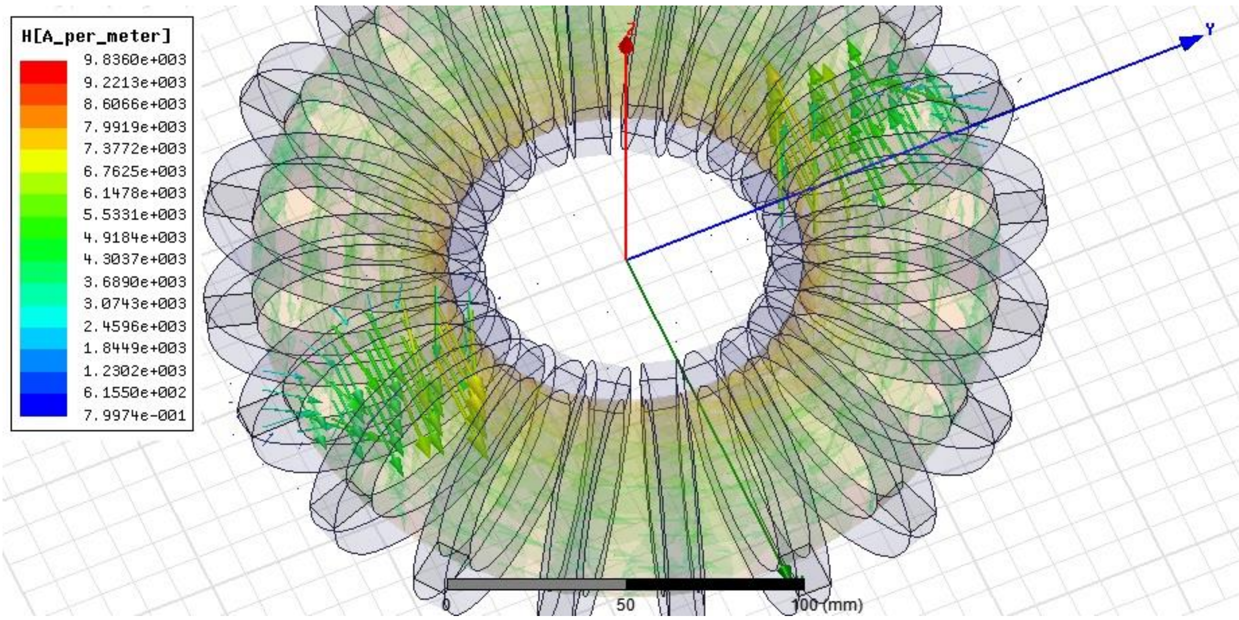
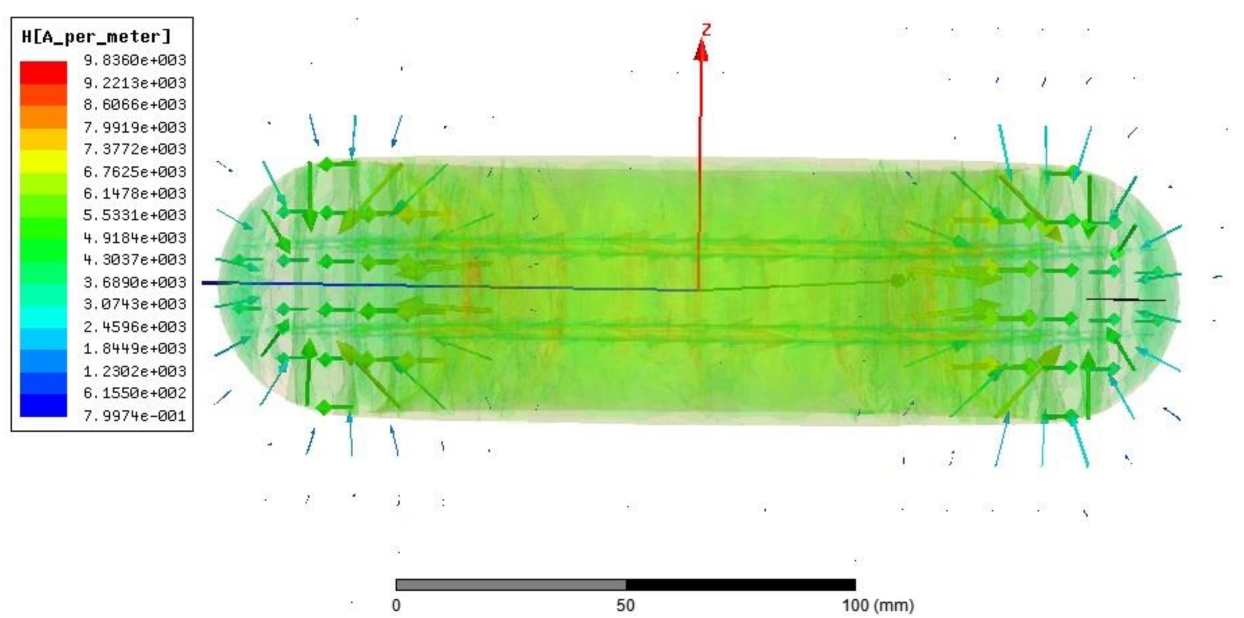


Figure 6.12Magnetic field intensity section view using 20 coils



Meshing

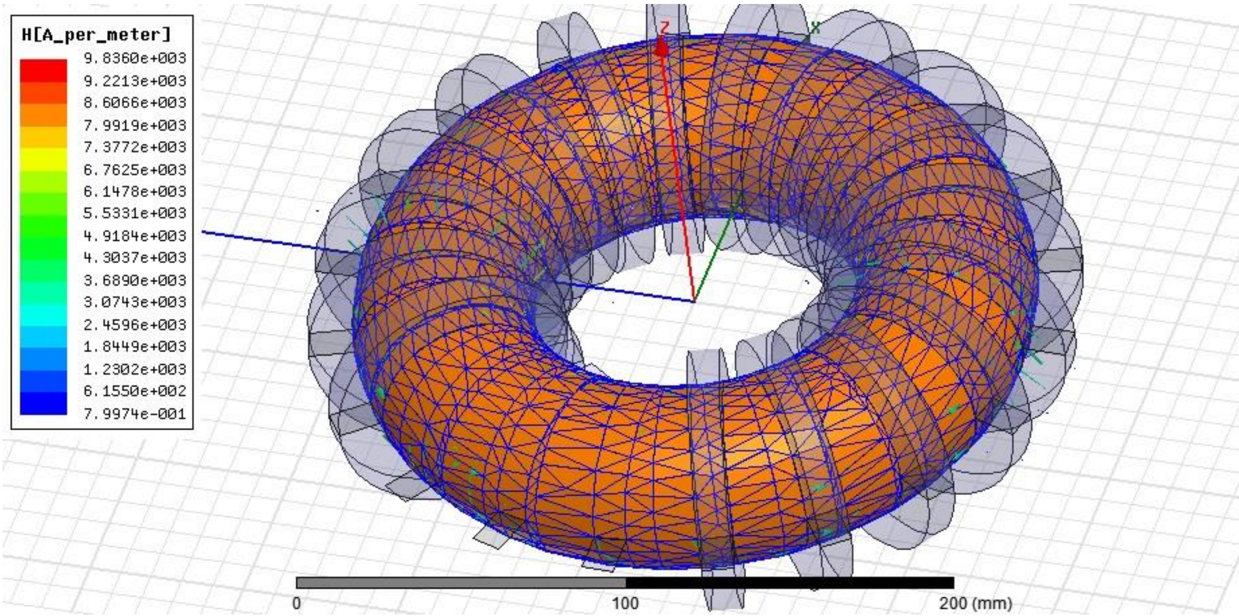


Figure 6.13-meshing using 20 coils

The above figure shows the meshing on the metallic surface which is in tetrahedral shape. The total number of tetrahedral is 30983. More the no. of tetrahedral the graph will be more confine.

Magnetic field vector around the surface

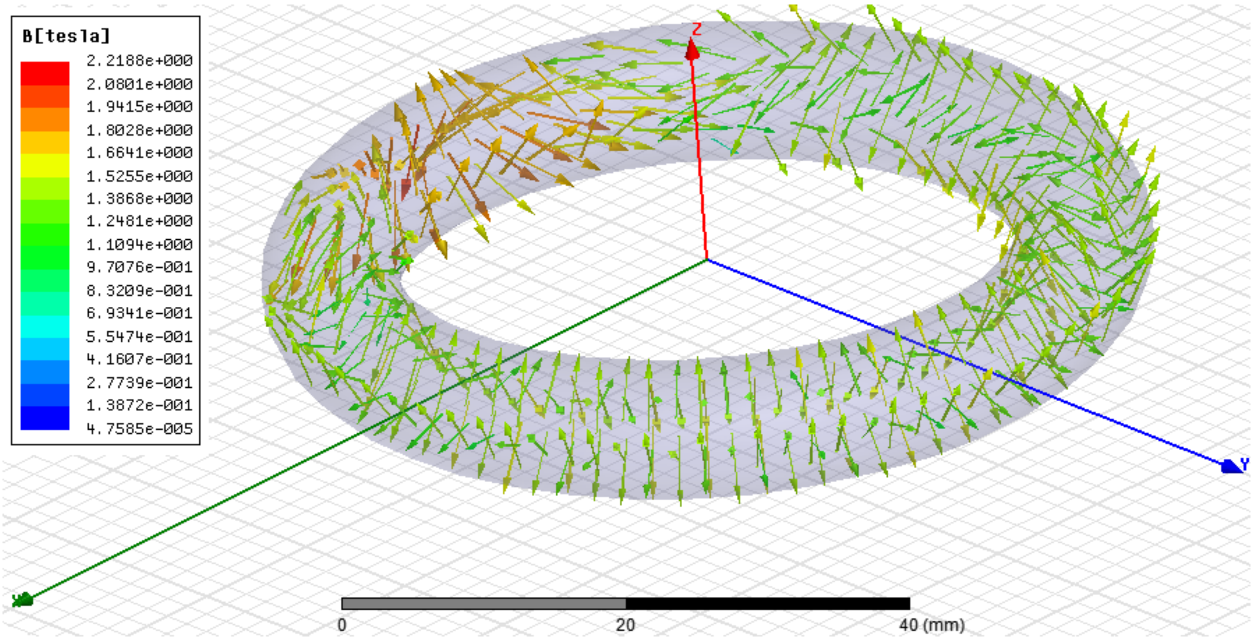


Figure 6.15-Magnetic field vecctor around the surface

The figure shows the magnetic field vector around the surface, so that it makes a cage like structure so that heat flux cannot pass out of the structure.

Plot

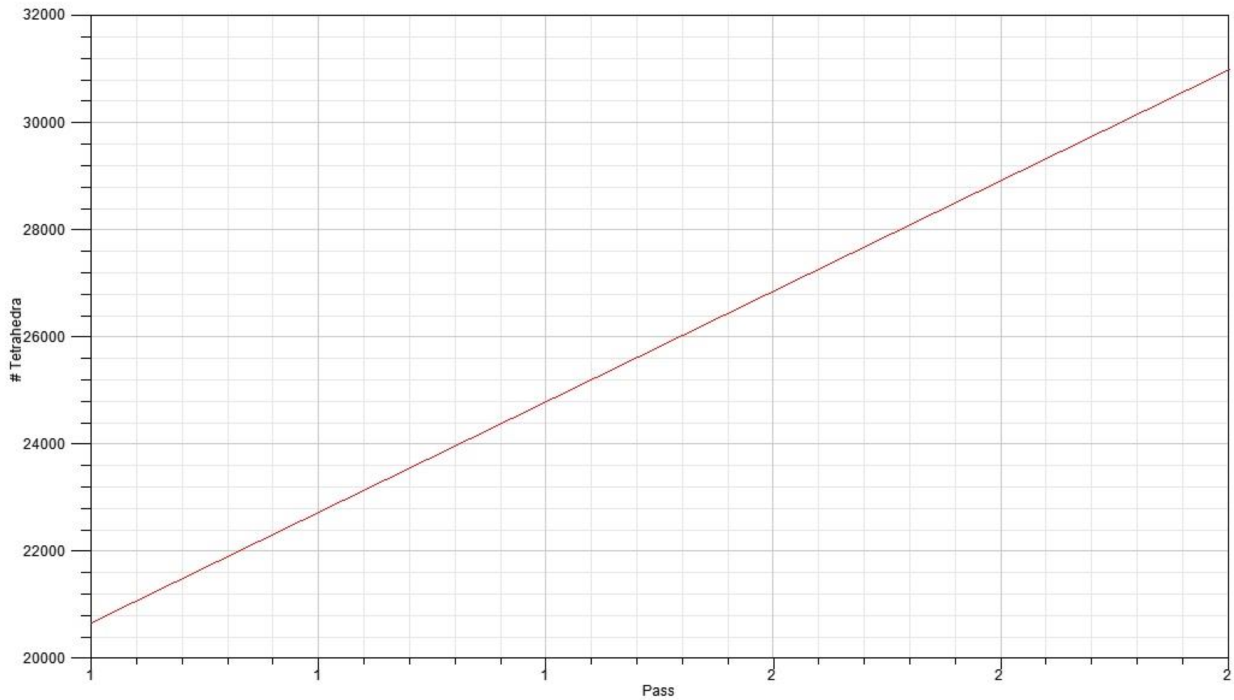


Figure 6.14 plot using 20 coils

Number of tetrahedral increased with increased in number of passes so the error will decreased. The total number of tetrahedral is 30983 with 3 numbers of passes more than the previous structure using single coil. This graph shows more linear then single coil.

Solution data

Adaptive pass

Task	Real Time	CPU Time	Memory	Information
				Executing from C:\Program Files\AnsysEM\AnsysEM15.0\Win64\MAXWELLCOMENGINE.exe
				Desired RAM limit not set.
Adaptive Pass 1				
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	469 K	2718 matrix, 0KB disk
Solver DRS	00:00:01	00:00:01	50.7 M	28284 matrix, 0KB disk
Solver DRS	00:00:00	00:00:01	50.7 M	28284 matrix, 0KB disk
Solver DRS	00:00:01	00:00:01	50.7 M	28284 matrix, 0KB disk
Solver DRS	00:00:00	00:00:01	50.7 M	28284 matrix, 0KB disk
adapt	00:00:14	00:00:13	107 M	20652 tetrahedra

Figure 6.15-Adaptive pass 1 using 20 coils

Task	Real Time	CPU Time	Memory	
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:01	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:00	00:00:00	488 K	2800 matrix, 0KB disk
Solver DRS	00:00:03	00:00:03	116 M	42208 matrix, 0KB disk
Solver DRS	00:00:02	00:00:02	116 M	42208 matrix, 0KB disk
Solver DRS	00:00:02	00:00:03	116 M	42208 matrix, 0KB disk
Solver DRS	00:00:02	00:00:02	116 M	42208 matrix, 0KB disk
adapt	00:00:21	00:00:19	156 M	30983 tetrahedra
				Adaptive Passes Converged
Solution Process				Elapsed time : 00:01:08 , Maxwell ComEngine Memory : 45.3 M
Total	00:00:51	00:00:52		Time: 05/01/2015 12:02:48, Status: Normal Completion

Figure 6.16- Adaptive pass 2 using 20 coils

The solution data is showing about time taken in conversing of solution it also tell about number of matrices solved during the conversion of solution and the memory used by those matrices which is shown in above figure.

Solution data

Total number of mesh elements: 30983

	Num Tets	Min edge length	Max edge length	RMS edge length	Min tet vol	Max tet vol	Mean tet vol	Std Devn (vol)
C0il	304	4.42431	19.4632	13.8246	0.455816	261.849	82.2692	64.2166
C0il_1	258	6.85397	18.3677	14.1772	3.39177	249.088	97.0041	62.5855
C0il_2	320	3.51593	19.8082	14.0167	1.05277	273.146	77.9758	64.5456
C0il_3	306	6.11269	19.0424	13.9647	0.783694	238.637	81.662	52.5555
C0il_4	231	6.77442	19.9501	14.8479	1.10632	249.135	108.344	68.7972
C0il_5	232	5.53132	19.2744	14.3804	0.0330791...	327.331	107.766	73.4707
C0il_6	297	6.37523	17.9948	13.9008	7.98461	237.967	84.0822	57.791
C0il_7	281	5.52138	18.7343	14.0087	1.08479	291.616	89.067	62.8415
C0il_8	254	5.18268	20.0047	14.0823	1.91136	370.602	98.5059	71.9655
C0il_9	296	5.18268	17.9948	14.3988	6.29868	239.951	84.3202	57.5318
C0il_10	300	5.52138	18.7343	14.0033	0.80205	355.98	83.3609	65.5904
C0il_11	254	5.82707	18.3677	14.2314	1.4454	307.345	98.5317	65.0119
C0il_12	289	5.30265	19.9459	14.6345	2.19454	243.718	86.3366	66.2208
C0il_13	290	6.31889	19.0424	13.8188	8.48777	238.848	86.1675	57.7524
C0il_14	258	6.22416	18.7343	14.1615	2.71698	247.212	97.0053	70.4424
C0il_15	205	5.69357	19.2744	15.3157	0.348072	327.331	121.943	70.0458
C0il_16	298	5.84159	17.9948	13.9514	8.8888	237.967	83.8001	56.4049
C0il_17	284	5.52138	19.0424	13.7902	1.08479	243.718	88.1597	64.8208
C0il_18	251	5.53944	18.1196	14.3753	1.47158	370.602	99.6743	73.5123
C0il_19	300	5.57258	18.7299	14.3592	7.49384	243.718	83.184	58.2408
core	10331	3.46796	36.6063	17.0395	0.420474	1339.5	116.657	111.659
Region	15144	4.32068	144.248	35.6866	0.0645374...	125814	2321.64	6825.76

Figure 6.17- solution data using 20 coils

Chapter 7

CONCLUSION

The purpose of Wendelstein 7-X is to evaluate the main components of a future fusion reactor built using stellarator technology, even if Wendelstein 7-X itself is not an economical fusion power plant. Stellarator has as their main advantage an intrinsically steady state magnetic field configuration. To resolve the main critical issues of W7-X design we have to do accurate prediction of system behavior. A new method has been developed for accurate prediction of structure is finite element method which is successfully implemented to adopt the designing of machine.

We can design the various structures using Ansys-Maxwell software and also can check its validation using this software. After the designing we can find the magnetic field on each and every part of structure in three dimensional views. We can also see the inside behavior of magnetic field and the direction of field in vector form. It also gives the meshing analysis od system with no. of tetrahedral created and solved. After analyzing different cases we have plots which can be compared and find the best solution.

- stellarators are inherently steady-state devices
- Used for continuous operation
- As the number of superconducting coil increased the field become more uniform
- Better economic efficiency

Chapter 8

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